NASA-CR-202808

A Robotic System for Inspecting HEPA Filters in a Large Cleanroom Facility at the NASA Kennedy Space Center

James E. Spencer, Jr.

I-NET Space Services
Kennedy Space Center, FL 32899

Pradeep K. Goel

NSK Corporation
Bloomingdale, IL 60108

Abstract

In this paper, the prime objective is to describe a custom 4-dof (degree-of-freedom) robotic arm capable of autonomously or telerobotically performing systematic HEPA filter inspection and certification in the Shuttle Launch Pad Payload Changeout Rooms (PCR's) on pads A and B at the Kennedy Space Center, Florida. This HEPA filter inspection robot (HFIR) has been designed to be easily deployable/transportable and is equipped with the necessary sensory devices, control hardware, software and man/machine interfaces needed to implement HEPA filter inspection reliably and efficiently without damaging the filters or colliding with existing PCR structures. In summary, the purpose of the HFIR is to implement an automated positioning system to move special inspection sensors in pre-defined or manual patterns for the purpose of identifying filter integrity and efficiency. This will ultimately relieve NASA Payload Operations from significant problems associated with time, cost and personnel safety, impacts realized during non-automated PCR HEPA filter certification.

1 Introduction

Fundamental to the definition of robotics, common applications of robotic systems in industry are driven by requirements to move parts, tools, sensors and materials through pre-programmed sequences to perform a variety of tasks. Although not a pre-requisite for robotic systems, many applications are also driven by additional requirements to automate processes that are in some way too dangerous and/or too costly for human's to perform manually. Such an application for a robotic system has been identified at the NASA Kennedy Space Center, and is being developed as an effective means to aid NASA engineers in further improving ground based launch related processing of the Space Shuttle and it's associated facilities [1]. This unique, custom robotic system has been developed by engineers in the Robotic Applications Development Laboratory at the NASA Kennedy Space Center, Florida to automate a very expensive, dangerous, and critical-time consuming task.

Sections 1.1, 1.2, and 1.3 describe the processes being automated and identify the work tasks and end-effector sensory devices. In Section 2, the manipulator architecture and joint descriptions are described, followed by a summary of off-line modeling, simulation and analysis using the IGRIP software package in Section 3. Section 4 gives an overview of the workcell operational hierarchy and necessary human-machine interfaces. Section 5 lists various performance characteristics and functional requirements which the overall system is expected to meet. Section 6 covers the results of filter inspection at Pad 39B of KSC and Section 7 the conclusions and a description of future work.

1.1 Process overview

In recent years, a need has been identified to automate the inspection and subsequent certification of HEPA (High Efficiency Particle Accumulator) air filters located in the Payload Changeout Rooms (PCR's) at the shuttle launch pads 39A and 39B at the NASA Kennedy Space Center. Each Payload Changeout Room (PCR) is approximately 50' (L) x 50' (W) and is outfitted with banks of HEPA filters mounted in the ceiling approximately 65' (H) from the PCR floor. Due to the atypical wear caused by excessive vibrations caused during launch, these filters require periodic inspection for any damage to their media (tears, cracks, etc.), support frames, gaskets and seals. More typical reasons for inspection are excessive deposition of particulate matter in the filter media. Nevertheless, all of the aforementioned anomalous conditions contribute to the deterioration of the filters' efficiency and overall integrity.

1.2 Problem significance

Currently, filter inspection is performed manually and takes about 120 man-hours to complete. This inspection task requires technicians to utilize ladders and special access platforms deployed on top of a six-story, movable structure inside the PCR. This massive structure, known as the PGHM (Payload Ground Handling Mechanism), is used to deploy and remove satellites and other payloads in and out of the Shuttle Orbiter's Cargo Bay. It is equipped with adequate power, fluid and personnel access systems which enable payload customers to verify and checkout payloads prior to launch. However, to provide technicians with adequate access to the HEPA filters in the ceiling of the PCR during inspection, the PGHM must be manually driven back and forth along floor/wall mounted rail supports/guides to facilitate technician access to the ceiling mounted HEPA filters. Additionally, this process is operationally costly because it requires approximately 25 spotters to watch various "potential trouble spots" for possible collisions between the PGHM and other PCR structures.

1.3 HEPA filter inspection process sensors

The HEPA filter inspection process sensor is a laser particle counter consisting of an iso-kinetic probe which intakes air samples to an electronics enclosure containing a microprocessor, laser diode, particle chamber, vacuum pump and other associated electronics. To perform an inspection, a technician must move the wand across the filter in a raster pattern (zig zag) at a rate of approximately 2 in/sec, while maintaining a 0.5 in. gap from the filter surface. The sensor system detects 0.3 micron (diameter) particles in the air stream and sounds an alarm whenever the count per cubic volume of air exceeds a pre-defined threshold. Additionally, an air flow velocity meter is used to determine leaks or potential leak conditions around filter gaskets & housings.

2 System description

In robotics terminology, the 4-dof HFIR architecture consists of a 3-dof cylindrical coordinate system robot (prismatic-revolute-prismatic) mounted on a 1-dof linear base. In order to cover the desired inspection envelope, the robot utilizes the I-beam rail of an existing 5-ton bridge crane in the PCR. A sketch of HFIR construction is shown in Fig. 1. The prismatic base (joint 1) is manually attached by technicians to the bridge crane I-beam rail and provides the major means of translational motion along the PCR ceiling. This joint is also referred to as the trolley. The trolley is composed of the halves that 'clam shell' around the I-beam of the PCR bridge crane. This trolley rolls along the beam via four 6 inch wheels. A direct-drive DC brushless servo motor drives two wheels on one side of the trolley. One wheel is directly interfaced to the motor shaft and a chain provides drive torque to the alternate wheel. Two 1.5 in. spring tensioned wheels on each side of the I-beam and 4 more on the bottom of the beam complete a stable base that supports the other 3 joint/link assemblies.

Joint 2 is suspended from joint 1 and is also prismatic. Considering an XYZ world coordinate system according to the right-hand rule, the trolley provides gross X-axis positioning, while the vertical drive assembly provides Z-axis motion. Its function is to maintain the pre-set 0.5 in. distance from the filter surface. This positioning is achieved in real-time through the utilization of a laser displacement sensor mounted in the process end-effector. This degree of freedom is also necessary during filter inspection to lower the end-effector below the bridge crane I-beam to allow Joint 3 to swing the end effector to the other side of the beam. Joint 2 then raises the end-effector back to its operational distance from the ceiling and inspection continues. The mechanics of joint 2 consist of a DC brushless servo motor connected to a 6:1 spur-gear reduction transmission. This transmission is connected to a 5 thread/in. lead screw and provides 26 inches of vertical stroke.

Joint 3 in the kinematic chain is known as the Rotary Drive. It is a revolute joint positioned at the bottom of joint 2, and is powered by the same type of direct-drive servo motor implemented on Joint 1. Its function is analogous to 'theta' in the polar coordinate system. It provides 346° rotation in a plane parallel to PCR ceiling. Joint 4, the horizontal arm drive, is prismatic and is coupled to joint 3. Joint 4 serves as the vector of the polar coordinate pair. It provides translational movement of the end-effector towards or away from the revolute joint 3. This joint is driven by a direct-drive servo motor coupled to a rack-and-pinion gear system. Four V-rollers or support bearings provide necessary stability throughout the 60 in. of arm travel.

3 IGRIP modeling simulation & analysis

For prototype arm design, optimum path planning and selection, it is essential to write manipulator kinematics as well as dynamics in order to simulate and analyze various tasks. In addition, dynamics of robotic systems assists in quantifying joint interactions, which facilitates the formulation and implementation of real-time closed-loop control systems for predefined trajectory following [2,3].

IGRIP [4] an off-line robot modeling, programming and simulation software package, provides easy solutions to robot kinematics, dynamic analysis and dynamic simulation. A kinematic model of the inverse solution for Θ_1, Θ_2 of the HFIR system is described below.

$$\Theta_1 = \mathrm{Atan}\,[PAY/PAX] * 180/\pi \qquad (\text{if } PAX>0) \tag{1}$$

$$\Theta_2 = \mathrm{Atan}\,[PBY/PAX] * 180/\pi \qquad (\text{if } PAX>0) \tag{2}$$

$$\Theta_1 = \mathrm{Atan}\,[PAY/PAX] * 180/\pi - 180 \qquad (\text{if } PAX<0) \tag{3}$$

$$\Theta_2 = \mathrm{Atan}\,[PBY/PAX] * 180/\pi - 180 \qquad (\text{if } PAX<0) \tag{4}$$

$$\Theta_1 = \{0,90,-90\} \quad (\text{if } PAX=0, \text{ if } (PAY=0,>0,<0)) \tag{5}$$

$$\Theta_2 = \{0,90,-90\} \quad (\text{if } PAX=0, \text{ if } (PAY=0,>0,<0)) \tag{6}$$

$$\text{where} \quad PAX = S_{56}*L_7+S_5*L_6+X \tag{7}$$

$$PAY = (Y+d_1) + /Q, \quad PBY = (Y+d1) - /Q \tag{8}$$

$$\text{where} \quad X = S_{356}*L_7+S_{35}*L_6+S_3*(L_4+d_4) \tag{9}$$

$$Y = -C_{356}*L_7 - C_{35}*L_6 - C_3*(L_4+d_4) - d_1 \quad (10)$$

$$Z = d_7+d_6-(L_2+d_2) \quad (11)$$

$$Q = (Y+d_1)^2+X^2-(S_{56}*L_7+S_5*L_6)^2 \quad (12)$$

$S_{356} = \sin(\Theta_3+\Theta_5+\Theta_6)$, $S_{35} = \sin(\Theta_3+\Theta_5)$

$C_{356} = \cos(\Theta_3+\Theta_5+\Theta_6)$, $C_{35} = \cos(\Theta_3+\Theta_5)$

The various parameters d_1, d_2, d_4, L_2, L_4, L_6, L_7, Θ_1, Θ_2, etc. are shown in Fig. 1.

The HFIR design documentation package was generated with the Engineering Modeling System (I/EMS), Intergraph's premier CAD software for mechanical design. All HFIR components and assemblies were created in I/EMS as solid models and then passed directly to IGRIP. The IGRIP model of the HFIR was used for optimization of each of the joint geometries, end-effector design, workspace analysis and motion path generation.

Once a kinematic solution was realized, the next step involved deriving a dynamics model for a multi-link, open-loop kinematic chain with rotational and/or prismatic joints. This included the effects of link inertia, gravity, centrifugal and coriolis forces, external tool loads and joint friction. The mass and inertia parameters for the links, motors and payload were specified by the user along with the joint friction constants. The dynamic analysis returned joint interaction forces and torques (for actuator saturation and duty cycle analysis). In addition, point reachability for various devices was verified within given joint limit constraints. Finally, in order to check the operation of the HFIR, IGRIP incorporated and implemented a collision avoidance algorithm.

4 Workcell operational hierarchy & I/F

An HFIR high level Operational and Interface diagram is shown in Fig. 2. The overall workcell constitutes three subsegments:

- Workcell Process Segment
- Workcell Integration Segment
- Robot Workcell Segment

4.1 Workcell process segment interface

This is a grouping of hardware, software, mechanism assemblies and personnel organizations responsible for ensuring that HFIR can procedurally, logistically and technically certify filters. The Workcell Process Segment interfaces with the Workcell Integration Segment and the Robot Workcell Segment.

4.2 Robot workcell segment

The Robot Workcell Segment includes hardware, software, mechanism assemblies and personnel / organizations responsible for developing the HFIR mechanism and control system capable of realizing an automated, robotic positioning system for the Workcell Process Segment.

4.3 Workcell integration segment

Lastly, the Workcell Integration Segment is the proving ground for the integrated HFIR filters inspection system. It is composed of the hardware, software, mechanism assemblies, and personnel/organizations responsible for facilitating the system integration, debug, test, checkout and personnel training for the HFIR system. Fig. 2 shows interaction and flow of information among the aforementioned three segments.

4.4 Typical operational scenario

The HFIR deployment begins when PCR technicians install the robot on one of the bridge crane rails in a shuttle payload Changeout room. HFIR will then be activated, internal calibration and checks are performed, and a filter sweep commences without human intervention. When scanning and inspection have been completed, the device can be commanded to move to a home position by remote control or a pre-programmed subroutine. A technician would then review the certification result for each filter, and accordingly advise the SPC (Shuttle Processing Contractor) ECS (Environmental Control System) Group for filter repair/replacement or approve the facility for the next payload changeout process. Fig. 3 illustrates a flow diagram describing sequence of events and checkups for deploying and operating HFIR.

5 Performance characteristics

The HFIR is capable of fulfilling the following functional requirements.

5.1 Automatic mechanism control system

The HFIR control system facilitates remote control of the robot arm by a very user friendly LabVIEW created Operator Interface located on the 6th level of the PGHM. The operator control cabinet consists of a computer monitor with an amplifier and video card support for live camera images and a customized IBM 486 DX2 computer. WINDOWS and a dedicated version of the LabVIEW graphically based data acquisition, control, and presentation software package present an easy interface to control automatic or manual robot motion. This intelligent, 4-Axis motion control system interprets high-level commands from the operator interface and accordingly commands individual axis servo drives.

5.2 Collision avoidance and detection

The HFIR system will support collision avoidance and detection systems to monitor known PCR ceiling obstacles. Upon full implementation of its control system, HFIR will be able to avoid known fixed obstacles in its path and impact detection sensors will also be employed to avoid unknown obstacles.

5.3 Deployability and transportability

The HFIR is designed such that two technicians can deploy it onto the 5-ton bridge crane rail. This system is also transportable to other launch pad PCR facilities.

5.4 Automated HEPA filter inspection

The HFIR system performs HEPA filter inspection autonomously by automatically positioning (moving along a pre-determined path) the particle counter while maintaining a 0.5 in fixed distance from the filter surface. While following these defined inspection paths, abundant data is acquired for later use in off-line analysis enabling HEPA filter certification.

5.5 Safety and reliability

The HFIR has been designed with electrical and mechanical redundancies required to assure the fail-safe operation. Each joint is equipped with optical end-of-travel (EOT) sensors which detect out-of-range motion as well as mechanical switches tied to the Emergency-Stop (E-Stop) circuit. Furthermore, mechanical hard-stops prevent motion beyond physical joint limits for the unlikely case that all other systems fail. Additionally, the control system has been designed with redundant command checks and power-on/power-down sequences to assure that a technician operator does not inadvertently create a dangerous or otherwise unsafe condition.

6 Results

On November 4, 1993, due to contamination issues during the highly sensitive Hubble repair mission, the NASA Environmental Control group requested that the HFIR be used to help collect filter data for use in evaluating the condition of the Pad 39B PCR. Although the HFIR was still in development, none of the filters inspected showed signs of excessive particle counts directly below the filter media (holes in the filters). Approximately 70% of the filters had total particle counts of less than 500 (0.3 micron) particles. The vast majority of these total counts came from the perimeter of the filters apparently caused by leakage between the filter and its support bracket. Five of the filters inspected had total counts of over 1000 (0.3 micron) particles (see figure 4). A generic motion profile was developed which could be used to coordinate the robot motion, required for scanning almost all of the accessible filters at Pad B. Figures 4 and 5 illustrate the results of 0.3 micron particle counts for all of the filters inspected using the HFIR system. Figure 4 displays a plot of the cumulative particle counts per filter inspected, and Figure 5 shows the cumulative total counts for one sample filter.

7 Conclusion and future work

In this paper, a robotic system for automating the HEPA filter inspection and certification is presented. This 4-dof manipulator is capable of covering 50'x50' ceiling outfitted with 66 HEPA filters inside a large payload processing facility at the Kennedy Space Center. The end-effector is equipped with a laser particle counter and air flow velocity meter to measure particle size and quantity, as well as detect any leaks in the filters or gasket housings.

IGRIP software package is employed to derive manipulator kinematics and dynamic equations. Current experimental runs involve the end-effector following specific motion profiles that navigate the robot mechanism around known facility structures and obstacles. The collision avoidance path planning necessary for safe operation and the control feedback structure are being refined. Upon completion of rigorous motion profile and repeatability testing, the system will be installed and certified as GSE (Ground Support Equipment), thus facilitating a very dangerous, time-intensive and expensive task that has been performed manually since the inception of the shuttle program.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support and assistance from Brent Reed and Gabor Tamasi of NASA, and Joe Looney, Rhonda J. McNulty, and Kirk Bigelow of I-NET, Kennedy Space Center, Florida. Also, technical support from Carey Cooper of Intergraph, Inc. in using IGRIP software is thankfully acknowledged. Lastly, the authors would like to thank NASA DE (Design Engineering) and the Engineering Support Contractor (ESC) for their engineering and management of the HFIR Project.

REFERENCES

1. Guide for Design Engineering of Ground Support Equipment and Facilities for use at Kennedy Space Center, Document #KSC-DE-512-SM.

2. Goel, P. K., "The Inverse Kinematics Solution, Closed-Form Dynamics and Simulation of Adept One Industrial Robot", Proc. International Conference on Robotics and Automation, Philadelphia, April 24-29, 1988, pp. 1688-1693.

3. Luh, J. Y. S., Walker, M. W. and Paul, R. P., "On-line Computational Scheme for Mechanical Manipulators", ASME Trans. J. Dynamic Systems, Measurement and Control, Vol. 102, June 1980, pp. 69-76.

4. IGRIP Simulation/Animation Software Package User's Manual, Deneb Robotics, Inc., Auburn Hills, MI.

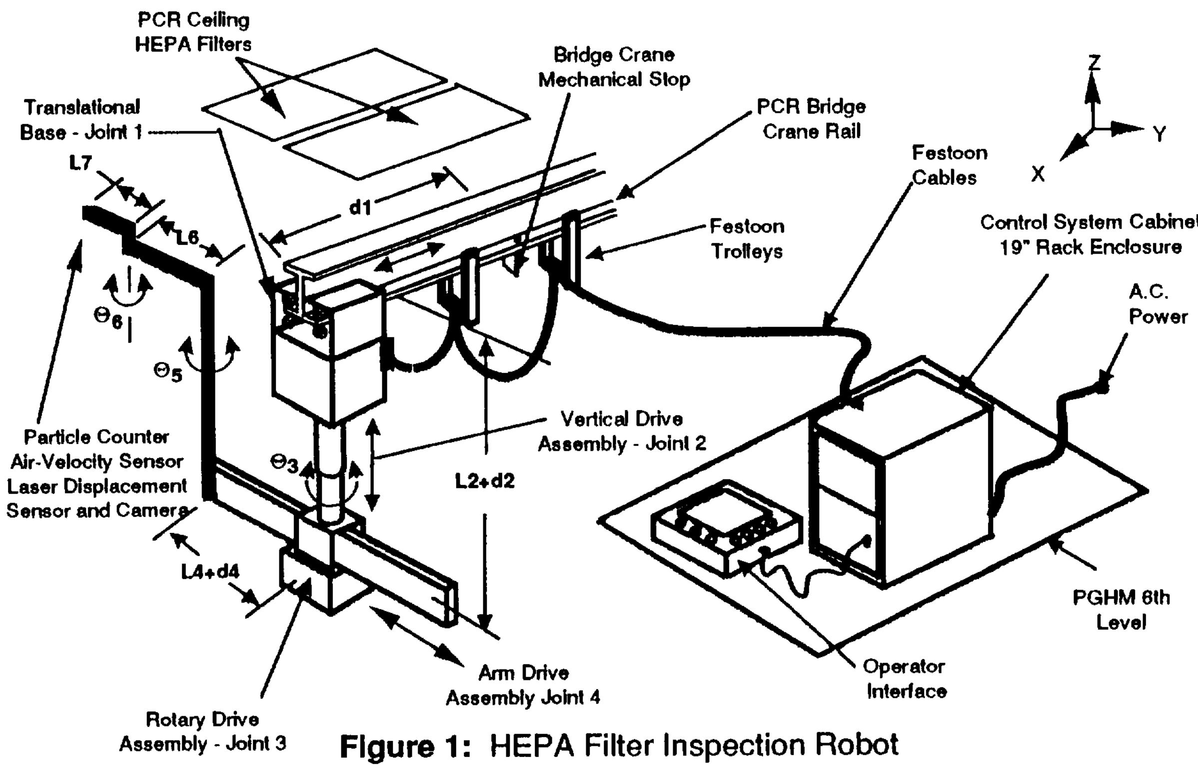

Figure 1: HEPA Filter Inspection Robot

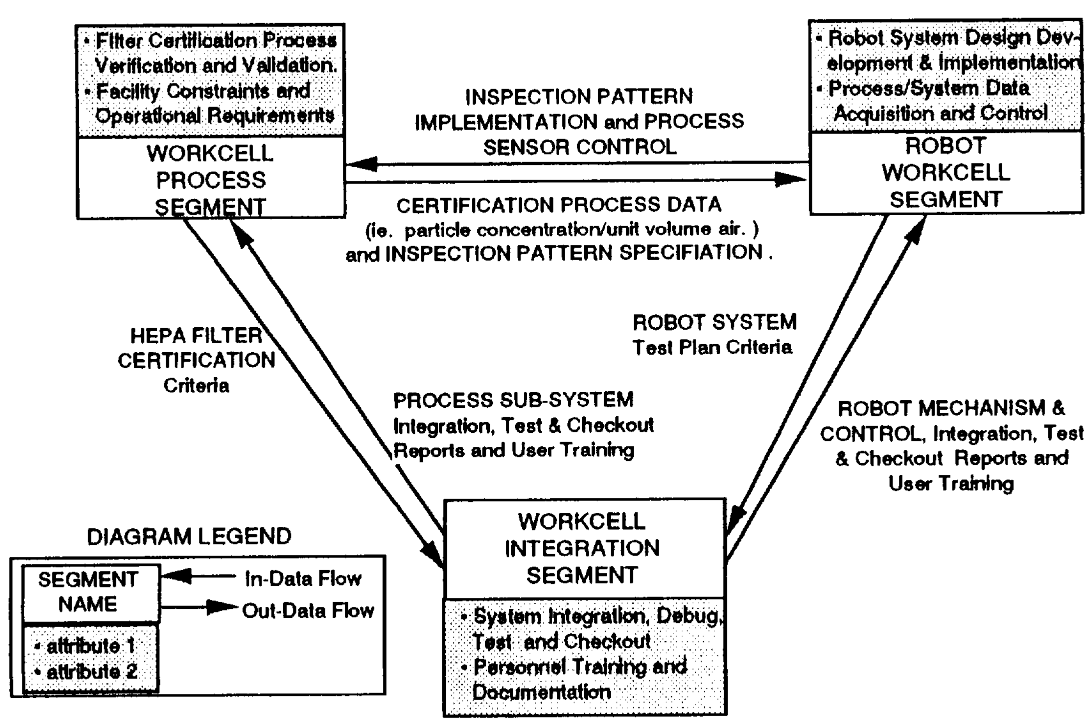

Figure 2: HFIR Top Level Functional Block Diagram

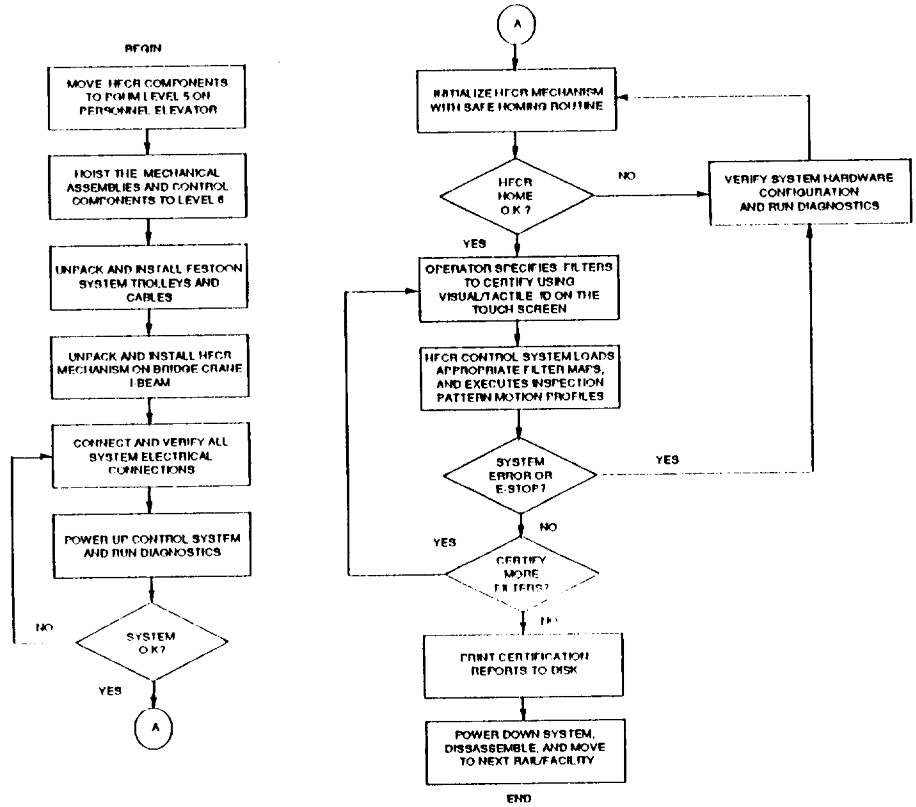

Figure 3: Portable and Deployable HFCR Operational Flow Diagram

Figure 4: Pad 39 B Cumulative Filter Counts

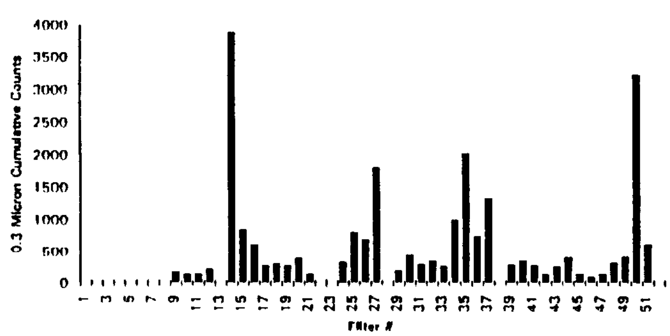

Figure 5: Filter # 20 Cumulative Particle Count